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METHOD FOR REAL-TIME DETERMINATION OF THE MASS OF PARTICLES PRESENT IN A PARTICLE FILTER OF A MOTOR VEHICLE

The invention relates to a method for real-time determination of the mass of particles present in a particle filter for the combustion engine of a motor vehicle.

The invention also relates to the use of this method in a method for management of an engine, especially engines running on lean mixture.

As it happens, the heterogeneity of the combustion processes in engines running on lean mixture has the effect of generating carbon particles which cannot be burned efficiently by the engine. That is expressed by the production of black exhaust smoke, characteristic of this type of engine, especially during starting phases and during hard accelerations. Compliance with future legislative standards requires the use of depollution systems capable of completely eliminating the particles as well as the nitrogen oxides.

For this purpose there is now available a semi-porous element forming a particle filter in the exhaust line, which permits the gaseous components to pass but retains the particulate compounds. In diesel engines, the fumes make us the basic constituent of these particulate compounds.

However, when the filter is considered to be full, a purge must be carried out in order to regenerate it. Thus each phase of retention of particles must be followed by a regeneration phase, during which the retained compounds are eliminated as non-polluting constituents (carbon dioxide and water). A new phase of accumulation of particulate compounds can then begin.

These particles are usually eliminated by combustion at a temperature of approximately 600°C. However, the exhaust gases of these engines rarely reach such a temperature during normal operation: it is necessary to raise the temperature specifically during the regeneration phase.

The means currently used proceed by creating a gaseous environment heated to a temperature of approximately 600°C. This operation makes it possible to favor spontaneous ignition of the carbon particles retained in the filter. These particles are then consumed with liberation of energy, which, depending on the conditions, can be transmitted by weight to

the bed of particles in the filter, to the various components of the depollution system (particle filter, holding box and jacket, piping, etc.), or else transported by the flow of gases discharged from the engine.

It is therefore important to know, at each instant, the mass of particles contained in the filter, particularly at the end of a regeneration, in order to optimize management of the sequence of regeneration phases and to monitor the integrity of the filter. In fact, combustion of an excessive quantity of particles may cause degradation or destruction of the filter by reason of the highly exothermic nature of this reaction.

In general, the mass of particles present in the filter is estimated by measuring the head loss caused by the filter, as described, for example, in French Patent 2774421. However, the mass estimated in this way is not always sufficiently precise, with the result that the filter can suffer degradation.

French Patent 2657649 discloses, for different operating conditions, different strategies for regeneration and for control of regeneration. More precisely, that document proposes to use an estimator of the mass of particles contained in the filter in order to implement or stop, as a function of engine speed and operating load, the different regeneration strategies used. The estimate of the mass of particles contained in the filter is determined using a difference between the mass of particles entering the filter from the engine emissions and the mass of particles consumed by combustion of the particles in the filter. These masses are determined directly from maps as a function of the operating parameters of the engine, and so they also are not always sufficiently precise that degradation of the filter can be avoided.

The object of the invention is to alleviate these drawbacks by proposing a method for real-time determination of the mass of particles present in a particle filter, wherein it is possible to achieve an improvement in the precision of calculation of the mass.

The method according to the invention also has the advantage that it needs only one temperature sensor at the inlet of the filter, which will therefore not suffer deterioration in the event that combustion of the particles were nevertheless to be too exothermic.

To this end, the object of the invention relates to a method for real-time determination of the mass of particles present in a particle filter installed in the exhaust line of an internal combustion engine, characterized in that the following sequence of operations is repeated at determined time intervals Δt:

(i) at the instant t, the temperature $T(t)$ of the exhaust gases at the inlet of the particle filter is measured using a temperature sensor,

(ii) at the instant t, the operating parameters of the engine are measured by means of sensors,

(iii) at the instant t, there are read, from pre-established tables, as a function of the operating parameters of the engine, the values of the following parameters: oxygen concentration $[O_2(t)]$ and nitrogen oxides concentration $[NO_x(t)]$ of the exhaust gases entering the particle filter, and the rate $F(t)$ of emission of particles from the engine,

(iv) at the instant t, using the kinetic laws of chemical reactions of combustion of particles, there is calculated the rate $V(t)$ of combustion of the particles in the particle filter by means of the following parameters: temperature $T(t)$, concentrations $[O_2(t)]$, $[NO_x(t)]$ of oxidizing agents, and mass $m(t - \Delta t)$ of particles present in the filter, obtained during the preceding cycle of operations at the instant $t - \Delta t$,

(v) at the instant t, there is calculated the mass $m(t)$ of particles present on the filter, using the mass $m(t - \Delta t)$ of particles obtained during the preceding cycle of operations according to the following formula:

$$m(t) = m(t - \Delta t) + [F(t) - V(t)] * \Delta t,$$

where Δt is the time interval between the instants $t - \Delta t$ and t,

(vi) the value calculated at the instant t for the mass $m(t)$ of particles present on the filter is recorded so that it can be used in the following sequence of operations at the instant $t + \Delta t$.

In another embodiment, one or more values of the parameters $[O_2(t)]$, $[NO_x(t)]$, $F(t)$ is or are obtained by measurement with sensors instead of by reading. Thus steps (ii) and (iii) can be omitted in the case that the three values are measured by sensors.

The invention also relates to the use of the method according to the invention for real-time determination of the mass of particles to monitor and/or control a method for management of the regeneration of a particle filter of a motor vehicle. Since the method according to the invention makes it possible to obtain a better evaluation of the mass of particles present in the filter at each instant, initiation of regeneration can be prevented if the quantity of particles detected would risk endangering the integrity of the filter following an excessive temperature rise during combustion.

In an alternative version, the determination method according to the invention is used when the temperature at the inlet of the filter ranges between approximately 250°C and 500°C. Outside this temperature range, a different method for determination of the mass can then be used, for example by employing a measurement of the loss of head in the particle filter.

The invention also relates to the use of the method according to the invention for real-time determination of the mass of particles in a method for management of the regeneration of a particle filter of a motor vehicle, to determine, for each operating point of the engine of a vehicle, a threshold mass of particles, below which the filter will tend to become loaded with particles and above which the rate of combustion of the particles in the filter will tend to increase.

The invention now is described with reference to the attached, non-limitative drawings, wherein:

- Fig. 1 is a schematic representation of an engine and its exhaust line equipped with a particle filter,

- Fig. 2 is the plot, as a function of time, of the mass (m_c) of particles present in the filter calculated according to the method of the invention and of the mass (m_p) of particles as measured by weighing.

Referring to Fig. 1, an engine 1 is connected to an exhaust-gas line 2 equipped with a particle filter 3. Upstream from filter 3 relative to the direction of circulation of the exhaust gases, an oxidation catalyst 4 is installed in the exhaust line in order to oxidize the nitric oxide in the exhaust gases to nitrogen oxides NO_x.

A temperature sensor 5 is provided in the exhaust line, at the inlet of particle filter 3.

Engine speed sensor 6 and engine load sensor 7 are provided in the engine to measure the speed Ne of the engine (number of revolutions per minute) and the load Q of the engine corresponding to the depression of the accelerator pedal.

Pressure sensors 8 and 9 are placed respectively at the inlet and outlet of particle filter 3.

The different sensors 5 to 9 are connected to a calculator 10, in which there are recorded tables or maps characteristic of the engine. These tables are pre-established by preliminary measurements performed for each engine.

The method for determination of the mass $m(t)$ of particles present in the filter at the instant t now is described.

This method consists in repeating, at determined time intervals Δt, the sequence of operations described below:

(i) In a first operation, there is measured, at the instant t, the temperature $T(t)$ of the exhaust gases at the inlet of the particle filter, by using temperature sensor 5. The value obtained is recorded in calculator 10.

(ii) In substantially simultaneous manner, there are measured, at the instant t, the operating parameters Ne and Q of the engine, by means of sensors 6 and 7. The measured values are also recorded in calculator 10.

(iii) Using the values Ne and Q measured at the instant t as inputs, calculator 10 then uses the tables pre-established as functions of the values Ne and Q to read the values of the following parameters: oxygen concentration $[O_2(t)]$ and nitrogen oxides concentration $[NO_x(t)]$ of the exhaust gases entering the particle filter, and the rate $F(t)$ of emission of particles from the engine. These read values correspond to the values at the instant t, and are recorded in calculator 10.

It is possible, however, to replace this operation of reading from the tables by measurements of a sensor placed at the inlet of the filter to measure the concentrations $[O_2(t)]$ and $[NO_x(t)]$ of oxygen and nitrogen oxides, and by a measurement of a particle analyzer (also placed at the inlet of the filter) to measure the rate $F(t)$ of emission of particles from the engine. Step (ii) can then be omitted.

(iv) Calculator 10 then proceeds to calculate the rate $V(t)$ of combustion of the particles in the particle filter at the instant t. As input data, the calculator uses the previously measured or read parameters: temperature $T(t)$, concentrations $[NO_x(t)]$ and $[O_2(t)]$ of nitrogen oxides and oxygen, as well as the mass $m(t - \Delta t)$ of particles present in the filter, obtained during the preceding cycle of operations at the instant $t - \Delta t$. For this purpose, the calculator uses the kinetic laws of the chemical reactions of combustion of particles, the formulas for which are pre-recorded. These laws will be described in detail hereinafter.

(v) In the following operation, the calculator calculates the mass $m(t)$ of particles present on the filter at the instant t, by using the mass $m(t - \Delta t)$ of particles obtained during the preceding cycle of operations at the instant $t - \Delta t$, by means of the following formula:

$m(t) = m(t - \Delta t) + [F(t) - V(t)] * \Delta t$, (E)

where Δt is the time interval between the instants $t - \Delta t$ and t.

(vi) The value calculated for the mass $m(t)$ of particles present on the filter at the instant t is then recorded in order to be used as input value in the sequence of operations following the instant $t + \Delta t$, particularly in operations (iv) and (v).

The sequence of operations described in the foregoing is then performed once again at the instant $t + \Delta t$.

At the initial instant t_i, when no mass $m(t - \Delta t)$ is available, the calculator then uses a mass $m_{pressure}(t_i)$ of particles present on the filter, estimated by using, in standard manner, the head loss or pressure difference ΔP between the inlet and outlet of filter 3 at the instant t_i. As an example, this pressure difference is calculated by using the measurements of pressure sensors 8 and 9 as input values.

It is also possible to resort to this estimated mass $m_{pressure}$ of particles at subsequent instants t of operation of the engine, for example for purposes of monitoring the mass $m(t)$ calculated according to the method of the invention.

In this way the mass of particles present on the filter is corrected in real time as a

function of the operating point of the engine, thus making it possible to achieve precision clearly superior to that of the known methods for determination of the mass.

We now will describe the kinetic laws used by the calculator according to the invention.

The reaction of combustion of the particles (soot) in a catalytic particle filter (active phase of the filter containing a catalyst) is initiated according to three different and complementary processes:

(1) The first process corresponds to the combustion of particles by oxidation by the nitrogen oxides NO_x contained in the exhaust gases or formed by reaction of the nitric oxide on platinum sites present in the active phase deposited by the filter. This reaction takes place in the range of approximately 250 to 500°C.

(2) The second process corresponds to the action of the catalyst of the active phase of the filter. The catalyst has an oxygen-donor character and supplies oxygen for oxidation of the particles. This process begins around 350°C.

(3) The third process corresponds to combustion of the particles by the oxygen present in the exhaust gases. Initiated at around 450 to 500°C, this process intensifies with temperature and in particular is responsible for active regeneration of the filter around 600°C.

The rates of reaction of these different processes can be expressed as kinetic equations in the following form (the rates are expressed in mg/s):

Process (1):

$$V_{NO_x} = K_1 e^{Ea1/RT(t)} \times [m(t - \Delta t)]^{a1} \times [NO_x(t)]^b$$

Process (2):

$$V_{O_{2catalyst}} = K_2 e^{Ea2/RT(t)} \times [m(t - \Delta t)]^{a2} \times [O_{2catalyst}(t)]^c$$

Process (3):

$$V_{O_2} = K_3 e^{Ea3/RT(t)} \times [m(t - \Delta t)]^{a3} \times [O_2(t)]^d$$

where:

- $T(t)$ represents the temperature measured at the inlet of the filter,

- $m(t - \Delta t)$ represents the mass of particles (in grams) present on the filter at the instant $t - \Delta t$ and calculated during the previously executed sequence of operations,

- $[NO_x(t)]$ represents the concentration of nitrogen oxides (in ppm) in the exhaust gases entering the filter at the instant t,

- $[O_{2catalyst}(t)]$ represents the concentration of oxygen (in per cent) available in the active phase ("wash coat") at the instant t,

- $[O_2(t)]$ represents the concentration of oxygen (in per cent) in the exhaust gases entering the filter at the instant t,

- K_1, K_2, K_3 are pre-exponential factors of the combustion reactions of processes (1), (2), (3) respectively,

- $Ea1$, $Ea2$, $Ea3$ are the activation energies of the combustion reactions of processes (1), (2), (3) respectively,

- $a1$, $a2$, $a3$, b, c, d are the partial reaction orders with respect to the mass of soot and of oxidizing agent (NO_x or O_2),

- R is the universal gas constant.

The kinetic parameters K_1, K_2, K_3, $Ea1$, $Ea2$, $Ea3$, $a1$, $a2$, $a3$, b, c, d are determined experimentally in standard manner.

In the case of the first rate equation:

$$V_{NO_x} = K_1 e^{Ea1/RT(t)} \times [m(t - \Delta t)]^{a1} \times [NO_x(t)]^b,$$

the following values can be used (for x = 2):

-5000 $< Ea1/R <$ -2000

0.2 $< a1 <$ 1

0.2 $< b <$ 2

The pre-exponential factor K_1 varies as a function of the concentration of nitrogen dioxide:

If $[NO_x(t)] >$ 90 ppm: $K_1 = ([NO_x(t)]^2 \times m) - ([NO_x(t)] \times n) + p,$

where: $10^{-8} < m < 10^{-6}$,

$10^{-6} < n < 10^{-4}$,

$10^{-4} < p < 10^{-2}$.

If $[NO_x(t)] <$ 90 ppm: $K_1 = q$, where $10^{-6} < q < 10^{-3}$.

In the case of the second rate equation:

$$V_{O_{2catalyst}} = K_2 e^{Ea2/RT(t)} \times [m(t - \Delta t)]^{a2} \times [O_{2catalyst}(t)]^c,$$

the following values can be used:

-2500 $<Ea2/R<$-1000

1 $<a2<$2.5

0 $<c<$1.5

The pre-exponential factor K_2 varies as a function of the temperature at the inlet of the filter or of the quantity of oxygen:

If $T(t)>260°C$: $K_2 = ([T(t)]^2 \times j) - ([T(t) \times k]) + l$,

where: $10^{-9} <j<10^{-7}$,

         $10^{-6} <k<10^{-4}$,

         $10^{-3} <p<10^{-2}$.

If $T(t)<260°C$ or $[O_2(t)]<4.6\%$: $K_2 = i$, where 0 $<i<$0.2.

In the case of the third rate equation:

$$V_{O_2} = K_3 e^{Ea3/RT(t)} \times [m(t-\Delta t)]^{a3} \times [O_2(t)]^d$$

the following values can be used:

-25000 $<Ea3/R<$-10000

0.5 $<a3<$2

0 $<d<$1.5

If $[O_2]<4.6\%$, $K_3 = e^g$, where 15 $<g<$30.

Otherwise $K_3 = n$, where 0 $<n<$0.2.

These parameters, as well as the kinetic rate formulas, are recorded in calculator 10 and used to calculate the rate $V(t)$ of combustion of the particles in the filter. This rate $V(t)$ is the sum of the rates of the three processes:

$$V(t) = V_{NO_x} + V_{O_2} + V_{O_{2catalyst}}.$$

For this case, it will be understood that only the concentrations $[NO_x(t)]$ and $[O_2(t)]$ can be measured if necessary by the sensors, but not $[O_{2catalyst}(t)]$. It is then not possible to omit step (ii) of measuring the operating parameters (Ne, Q) of the engine.

When filter 3 does not contain any catalyst, then the combustion reaction according to process (2) does not take place. The combustion rate is then:

$$V(t) = V_{NO_x} + V_{O_2}.$$

The value calculated in this way for the combustion rate can be used for calculating the mass $m(t)$ of particles present in the filter, by using equation (E).

Fig. 2 shows the good agreement between the mass (m) of particles calculated according to the method of the invention and the mass (m_p) of particles effectively present in the filter and determined by weighing.

The sequence of operations used to calculate the mass of particles according to the invention is preferably executed at time intervals Δt on the order of one second. Of course, it is possible to use other values.